Vector meson production at the LHC

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Abstract. By using a Regge-pole model for vector meson production (VMP), that successfully describes the HERA data, we analyse the connection of VMP cross sections in photon-induced reactions at HERA with those in ultra-peripheral collisions at the Large Hadron Collider (LHC). The role of the low-energy behaviour of VMP cross sections in γp collisions is scrutinized.

ULTRA-PERIPHERAL COLLISIONS

Following the shut-down of HERA, interest in exclusive diffractive vector meson production (VMP) has shifted to the LHC. In ultra-peripheral reactions $h_1h_2 \to h_1Vh_2$, (where h_i stands for hadrons or nuclei, e.g. Pb, Au, etc.) one of the hadrons (or nuclei) emits quasi-real photons that interact with the other proton/nucleus in a similar way as in ep collisions at HERA. Hence the knowledge of the $\gamma p \to Vp$ cross section accumulated at HERA is useful at the LHC. The second ingredient is the photon flux emitted by the proton (or nucleon). The importance of this class of reactions was recognized in early 70-ies (two-photon reactions in those times) [1, 2]. In particular, in those papers the photon flux was calculated. For a contemporary review on these calculations, see for instance Ref. [3].

In the present paper we continue studies of VPM in ultra-peripheral collisions at the LHC started in Ref. [4], where references to previous papers can be also found. In particular, we make predictions for J/ψ and $\psi(2S)$ productions in pp scattering. We also extend the analysis to the lower energies for the photon-proton cross section, in order to scrutinize the $\frac{d\sigma^{pp}}{dy}$ cross section behavior at that kinematic regime.

The rapidity distribution of the cross section of vector meson production (VMP) in the reaction $h_1h_2 \to h_1Vh_2$, as shown in Fig. 1, can be written in a factorized form, i.e. it can be presented as a product of the photon flux and photon-proton cross section [3, 4].
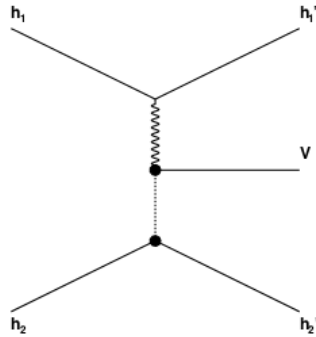

FIGURE 1. Feynman diagram of vector meson production in hadronic collision.

The $\gamma p \to Vp$ cross section (V stands for a vector meson) depends on three variables: the total energy W of the γp system, the squared momentum transfer t and $\widetilde{Q}^2 = Q^2 + M_V^2$, where $Q^2 = -q^2$ is the photon virtuality. Since, in

ultraperipheral[1] collisions photons are nearly real ($Q^2 \approx 0$), the vector meson mass M_V^2 remains the only measure of "hardness". The t-dependence (the shape of the diffraction cone) is known to be nearly exponential. It can be either integrated, or kept explicit. The integrated $\sigma_{\gamma p \rightarrow VP}(\tilde{Q}^2, W)$ and differential $\frac{d\sigma(t)}{dt}$ cross sections are well known from HERA measurements.

As mentioned, the differential cross section as function of rapidity can be factorized:[2]

$$\frac{d\sigma^{h_1 h_2 \rightarrow h_1 V h_2}}{dy} = r(y) E_{\gamma_+} \frac{dN_{\gamma_+ h_1}}{dE_{\gamma_+}} \sigma^{\gamma h_2 \rightarrow V h_2}(E_{\gamma_+}) + r(y) E_{\gamma_-} \frac{dN_{\gamma_- h_2}}{dE_{\gamma_-}} \sigma^{\gamma h_1 \rightarrow V h_1}(E_{\gamma_-}). \tag{1}$$

Here $\frac{dN_{\gamma h}}{dE_\gamma} = \frac{\alpha_{em}}{2\pi E_\gamma}\left[1 + (1 - \frac{2E_\gamma}{W_{pp}})^2\right]\left(\ln\Omega - \frac{11}{6} + \frac{3}{\Omega} - \frac{3}{2\Omega^2} + \frac{1}{3\Omega^3}\right)$ is the "equivalent" photon flux [3], $\sigma^{\gamma h_i \rightarrow V h_i}(E_\gamma)$ is the total (i.e. integrated over t) exclusive VMP cross section (the same as at HERA [5, 6]), $r(y)$ is the rapidity gap survival correction, and $E_\gamma = W_{\gamma p}^2/(2W_{pp})$ is the photon energy, with $E_{\gamma min} = M_V^2/(4\gamma_L m_p)$, where $\gamma_L = W_{pp}/(2m_p)$ is the Lorentz factor (Lorentz boost of a single beam). Furthermore, $\Omega = 1 + Q_0^2/Q_{min}^2$, $Q_{min}^2 = (E_\gamma/\gamma_L)^2$, $Q_0^2 = 0.71 \text{GeV}^2$, $x = M_V e^{-y}/W_{pp}$, and $y = \ln(2E_\gamma/m_V)$. The signs $+$ or $-$ near E_γ and N_γ in Eq. (1) correspond to the particular proton, to which the photon flux is attached.

For definiteness we assume that: a) the colliding particles are protons; b) the produced vector meson V is J/ψ (or $\psi(2S)$), and c) the collision energy $W_{pp} = 7 \text{TeV}$.

Corrections for rapidity gap survival probabilities

The predictions may be modified by corrections due to initial and final state interactions, alternatively called rescattering corrections. Since this is a complicated and controversial issue *per se*, deserving special studies beyond the scope of the present paper, here we use only familiar results from the literature: the standard prescription is to multiply the scattering amplitude by a factor (smaller than one), depending on energy and eventually other kinematic variables [7]. In this work we use a constant correction coefficient $r = 0.8$ (a variable one, $r(y) = 0.85 - 0.1|y|/3$ was used in Ref. [8]).

THE $\gamma p \rightarrow V p$ CROSS SECTION

In this Section we present theoretical predictions for J/ψ and $\psi(2S)$ production in γp scattering. In doing so, we use the so-called Reggeometric model [5], the two-component ("soft" and "hard") Pomeron model [6] and a model [9] including the low-energy region. In the Reggeometric model we use

$$\sigma_{\gamma p \rightarrow J/\psi} = A_0^2 \frac{(W_{\gamma p}/W_0)^{4(\alpha_0 - 1)}}{(1 + \tilde{Q}^2/Q_0^2)^{2n}\left[4\alpha' \ln(W_{\gamma p}/W_0) + 4\left(\frac{a}{Q^2} + \frac{b}{2m_p^2}\right)\right]}, \tag{2}$$

where $\tilde{Q}^2 = Q^2 + m_V^2$, with the parameters $A_0 = 29.8\sqrt{\text{nb}}/\text{GeV}$, $Q_0^2 = 2.1 \text{GeV}^2$, $n = 1.37$, $\alpha_0 = 1.20$, $\alpha' = 0.17 \text{GeV}^{-2}$, $a = 1.01 \text{GeV}^2$, $b = 0.44 \text{GeV}^2$, $W_0 = 1 \text{GeV}^2$ (Ref. [6], Table II, J/ψ production).

The models above, apart from W and t, contain also dependence on the virtuality Q^2 and the mass of the vector meson M_V, relevant in extensions to the $\psi(2S)$ production cross section. As shown in Ref. [6], to obtain the $\psi(2S)$ cross section one needs also an appropriate normalization factor, which is expected to be close to $f_{\psi(2S)} = \frac{m_{\psi(2S)}\Gamma(\psi(2S) \rightarrow e^+ e^-)}{m_{J/\psi}\Gamma(J/\psi \rightarrow e^+ e^-)} = 0.5$. According to a fit of $\frac{\sigma^{\gamma p \rightarrow p + \psi(2S)}(W)}{\sigma^{\gamma p \rightarrow p + J/\psi}(W)}$ to the data [10] with a two-component Pomeron model, the value $f_{\psi(2S)} = 0.4$ is reasonable. Thus, if the formula for the cross section $\sigma(W, Q^2, m_{J/\psi})$ describes $\gamma p \rightarrow J/\psi + p$ production, then $f_{\psi(2S)}\sigma(W, Q^2, m_{\psi(2S)})$ should describe $\gamma p \rightarrow \psi(2S) + p$ production as well.

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[1] In ultraperipheral collisions the impact parameter $b \gg R_1 + R_2$, i.e. the closest distance between the centers of the colliding particles/nuclei, $R_{1,2}$ being their radii.

[2] More precisely, the cross section can be presented as the sum of two factorized terms, depending on the photon or Pomeron emitted by the relevant proton.
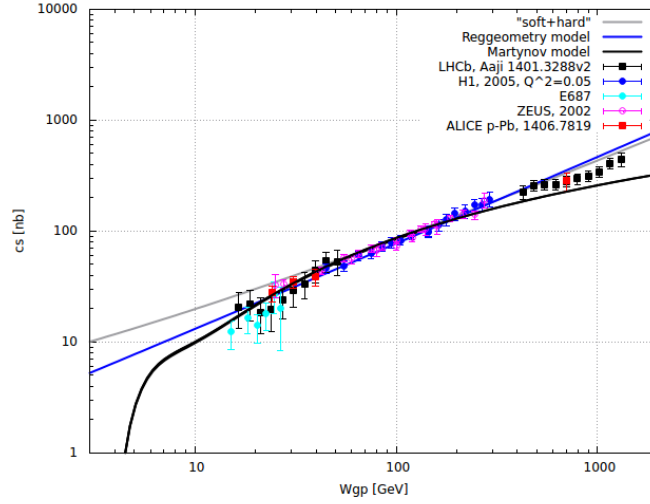
FIGURE 2. Comparison of LHCb [8], ALICE [11] and HERA [12] data on J/ψ photoproduction cross section with the two component Pomeron model [6], the Reggeometry model [5] and the Martynov model [9].

The above mentioned models fitted to the HERA electron-proton VMP data can be applied also to the VMP in hadron-hadron scattering. The LHCb Collaboration has recently measured ultraperipheral J/ψ and $\psi(2S)$ photoproduction cross sections in pp-scattering (at 7 TeV) [8]. From these data the γp cross section can be extracted. In Fig. 2 we compare the LHCb [8], ALICE [11] and HERA [12] data on J/ψ photoproduction to the theoretical predictions.

RAPIDITY DISTRIBUTIONS

To calculate the rapidity distribution $\frac{d\sigma}{dy}^{pp\to pVp}(y)$ we use Eq. (1), with an appropriate γp cross section $\sigma^{\gamma p\to Vp}(W_{\gamma p})$. In Fig. 3 we show the LHCb [8] data together with the predictions for the J/ψ and the $\psi(2S)$ differential rapidity cross sections obtained from the Regge model [5], the two-component Pomeron model [6] and that of Ref. [9]. The rapidity gap survival factor $r(y) = 0.8$ was used.
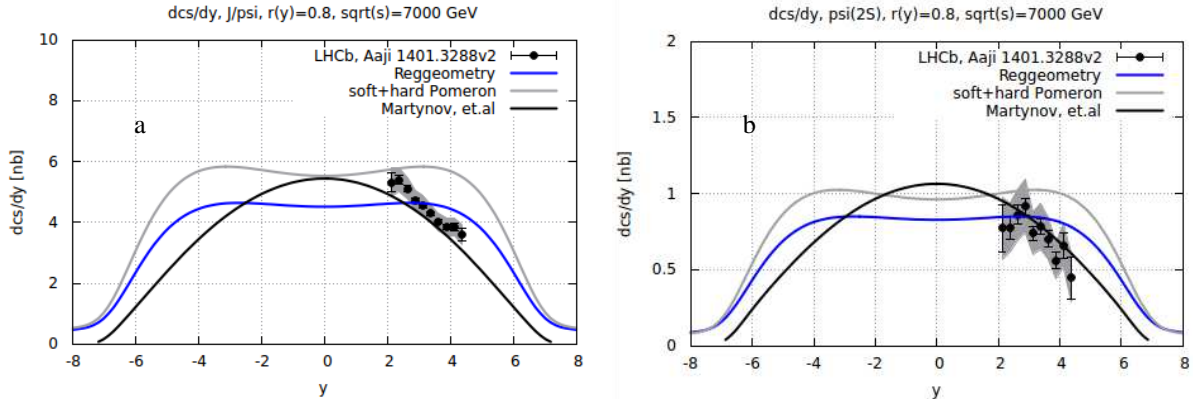

FIGURE 3. Comparison of the LHCb [8] data on (a) J/ψ and (b) $\psi(2S)$ photoproduction cross section as a function of rapidity, y, with the two-component Pomeron model [6], the Reggeometric model [5] and that of Ref. [9]. An absorption correction $r(y) = 0.8$ was applied to theoretical predictions.

The energy of the γp system $W_{\gamma p}$ is related to rapidity y via $W_{\gamma p}^{\pm} = \sqrt{M_{J/\psi}W_{pp}e^{\pm y}}$ (the choice of the sign depends on the propagation direction of γ). Hence, the differential rapidity cross section $\frac{d\sigma}{dy}$, in the range $y \in [2, 4.5]$ at energy $W_{pp} = 7$ TeV, needs the knowledge of the integrated cross section $\sigma(W_{\gamma p})$ in the range $W_{\gamma p} \in [15.5, 54] \cup$

$[400, 1397]$ GeV. Fig. 3(a) and 3(b) show how sensitive the differential $\frac{d\sigma}{dy}$ cross section predictions are to the choice of $\sigma(W_{\gamma p})$ cross sections (see also Fig. 2).

The curve of the model [9] for J/ψ (and its extension for $\psi(2S)$) gives better description of the differential rapidity cross section than the Reggeometric and the two-component Pomeron models, but it seems to underestimate the J/ψ data (see Fig. 3(a)). This may result from underestimation of the γp cross sections by the model [9] at higher energies (see Fig. 2). To properly describe the rapidity distribution of VMP cross section in pp scattering, we need to correctly describe the γp VMP cross section in the whole energy region. Each γp energy range corresponds to its particular rapidity range.

CONCLUSIONS AND PROSPECTS

Summary of the reported results. We have compared several theoretical models: the Reggeometric, the power-like, and the Regge-pole model of Ref. [9] with the recent LHCb data on J/ψ and $\psi(2S)$ photoproduction in ultraperipheral pp collisions at LHCb [8]. From the integrated γp cross sections $\sigma(W_{\gamma p})$, obtained at HERA, we have calculated the rapidity distribution of differential $\frac{d\sigma}{dy}^{pp \to pVp}(y)$ cross section.

Prospects/problems. In the near future the following items are on the agenda:

1. A feasible formalism relating nucleon and nuclear reactions should be elaborated within the Glauber theory of multiple scattering. Some work in this direction has already been done in Refs. [3] a) and [13].

2. HERA had provided rich information on the Q^2 and t dependence of VMP production, and sofisticated models exist (see, for example, Ref. [6] and references therein) reproducing this rich and non-trivial dependence. This is not known yet at the LHC: in nuclear collisions the Q^2 (by kinematics, Q^2 in nuclear collisions is limited to less than $0.5\,\mathrm{GeV}^2$) and the t dependence are practically unknown. We hope that the experimental situation will improve.

3. The f trajectory may append/replace the Pomeron exchange, and similarly the photon flux may be appended by the flux of ω's and of the Odderon trajectories, opening new channels and thus making the picture more complicated, but, at the same time, more interesting.

ACKNOWLEDGMENTS

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